

TASTE. II. A new observational study of transit time variations in HAT-P-13b[★]

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ABSTRACT

TASTE (The Asiago Search for Transit timing variations of Exoplanets) project is collecting high-precision, short-cadence light curves for a selected sample of transiting exoplanets. It has been claimed that the hot jupiter HAT-P-13b suddenly deviated from a linear ephemeris by ~ 20 min, implying that there is a perturber in the system. Using five new transits, we discuss the plausibility of this transit time variation (TTV), and show that a periodic signal should not be excluded. More follow-up observations are required to constrain the mass and the orbit of the hypothetical perturber.

Key words. techniques: photometric – stars: planetary systems – stars: individual: HAT-P-13

1. Introduction

Photometric transits represent a great opportunity to discover and characterize extrasolar planets. They are, for instance, the only direct method to estimate the planetary radius and to constrain other important physical and orbital parameters (Winn 2010). In principle, a single planet orbiting the host star in a Keplerian orbit is expected to transit at strictly periodic time intervals, unless it is perturbed by a third body (Holman & Murray 2005). By performing accurate measurements of the central instant time of a known transiting planet, it would be possible to detect deviations from a linear ephemeris, and to infer the parameters of the perturber (Agol et al. 2005). Such a search for other bodies via transit time variations (TTV) is very sensitive to low-mass planets when they are locked in low-order orbital resonances. In these orbits, even earth-mass perturbers would cause TTVs of the order of a few minutes, i.e. easily detectable with ground-based techniques.

In the past few years, some authors have claimed to have detected TTVs using ground-based facilities, for instance from WASP-3b (Maciejewski et al. 2010), WASP-10b (Maciejewski et al. 2011), and WASP-5b (Fukui et al. 2011), though none have been confirmed so far. In contrast, the Kepler mission found undisputable mutual TTVs for the double transiting system Kepler-9b,c (Holman et al. 2010) and for five among six planets transiting on Kepler-11 (Lissauer et al. 2011), which has lead to the validation of those planets, as well as a deep characterization of their planetary systems.

Pál et al. (2011) claimed to have detected an unusually large TTV in HAT-P-13b. The G4V star HAT-P-13 hosts a multiple planetary system, and was the first multiple system discovered with a transiting planet. HAT-P-13b is a classical “hot jupiter”

($M = 0.85M_J$, $R = 1.28R_J$) transiting every ~ 2.91 days, while HAT-P-13c is an outer, massive companion ($M \sin i \sim 15M_J$, $P = 428.5$ days) detected only with radial velocity (RV) measurements (Bakos et al. 2009). A 2010 multi-site campaign designed to detect the transit of HAT-P-13c yielded a null result with a 65-72% significance level (Szabó et al. 2010). A long-term RV trend of HAT-P-13 was observed by Winn et al. (2010) and interpreted as evidence of a third companion with an even longer orbital period, still to be constrained.

The TTV claimed by Pál et al. (2011) appears to be a sudden deviation of the timings of three transits (by 3.3, 5.5, 8.4 σ) from the linear ephemeris evaluated using the previous data. All the three newly added points are consistent with each other. The “switch” has an amplitude of the order of ~ 0.015 days (Fig. 2, top left panel). This would make it the largest TTV claimed from the ground. The presence of the outer companion HAT-P-13c does not explain such a perturbation, as its expected TTV would have an amplitude of a few seconds and a ~ 430 d period, while the measurements before 2011 are in agreement with a constant ephemeris. An intriguing possibility is that this behaviour is induced by a long-period, massive companion on a very eccentric orbit. Eccentric perturbers are known to cause sudden “spikes” in an otherwise constant $O-C$ diagram (Holman & Murray 2005).

Unfortunately, the available data allow us to constrain the orbital parameters of neither the hypothetical perturber, nor its mass. The transit of HAT-P-13b is shallow ($\Delta m \sim 0.008$ mag) and long ($d \sim 194$ min), i.e. very difficult to monitor. Few measurements were made before 2011, and most with an estimated timing accuracy $\gg 1$ min. Two out of three transits from Pál et al. (2011) show a considerable amount of systematic errors, and one is partial, lacking the egress. Their detection urgently needs a confirmation: if confirmed, efforts should be made to monitor other

[★] Based on observations collected at Asiago observatory.

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Table 1. Summary of the observed transits of HAT-P-13b at the Asiago 1.82m telescope.

eve. date	UT obs. time	airmass	exptime (s)	cadence (s)	duty-cycle	frames	notes
2011 Jan 2	19:46–23:40	1.63–1.03	8	9.7	83%	1451	clouds
2011 Jan 31	23:08–04:18	1.00–1.58	3, 5	6.6	75%	2810	clear
2011 Feb 3	21:07–03:30	1.05–1.00–1.23	5	6.7	75%	2902	some veils
2011 Feb 6	18:53–23:40	1.29–1.00–1.01	4, 5	5.8	71%	2940	clear
2011 Feb 9	17:29–22:31	1.57–1.00	4, 5	6.0	72%	3011	clear, twilight

Notes. The columns give: the “evening date” of the observation, the UT time span of the photometric series, the airmass evolution, the exposure time and the average net cadence in s, the overall duty-cycle, the number of frames gathered, and the sky conditions at the time.

transits of HAT-P-13b in the near future, to assess the parameters and the nature (substellar or planetary) of the perturber.

In this Paper, we report five new high-precision light curves of HAT-P-13b, observed in January and February 2011 with the Asiago 1.82m telescope. Four of those transits are consecutive, and their estimated timing accuracy is the highest ever achieved for this target. We confirm the deviation with respect to the ephemeris from Szabó et al. (2010) reported by Pál et al. (2011). No ephemeris with a constant period can be fitted to the data with an acceptable χ^2 . The observed deviation is still highly unconstrained. We note that a long-period, sinusoidal TTV can be fitted to the $O - C$ points, with only one significant outlier.

2. Observations

All the observations reported here were made as part of the TASTE (The Asiago Search for Transit timing variations of Exoplanets) project (Nascimbeni et al. 2011). TASTE is collecting high-precision, short-cadence light curves for a selected sample of transiting exoplanets, to discover low-mass planetary companions or exomoons with the TTV/TDV method (transit time/duration variation). We refer to that paper for a detailed description of our instrumental setup, observing strategy, and data reduction/analysis. HAT-P-13b is among the sample we are following.

We collected five transit light curves of HAT-P-13b using the AFOSC imager with its new E2V 42-20 CCD detector mounted at the Asiago 1.82m telescope¹. An observation log is shown in Table 1. All the observations were made using a standard Cousins R filter and 4×4 binning. We employed binning and windowing to speed up the readout and decrease as much as possible the technical “dead” times between the exposures. We achieved an average $> 70\%$ duty-cycle and a < 10 s net cadence for all our photometric series. We acquired both sky- and dome flat-field frames during each night; bias and dark frames were taken at both the beginning and the end of a light curve to constrain possible instrumental drifts.

Stellar profiles were defocused to $\sim 4 - 6''$ FWHM (that is, over ~ 1300 physical pixels) in order to minimize systematic errors arising from imperfect flat-field correction, guiding drifts, and pixel-to-pixel inhomogeneity. The $9' \times 2'.6$ CCD window that we read included HAT-P-13 as well as the main reference star TYC 3416-1608-1, a star with a magnitude and colour similar to HAT-P-13 ($V_T = 10.80$ versus (vs.) 10.50 and $B_T - V_T = 0.81$ vs. 0.52).

3. Data reduction and analysis

We performed differential aperture photometry on HAT-P-13 using STARSKY (Nascimbeni et al. 2011), an independent

Table 2. Best-fit values of the central instant T_0 for the five reported new transits of HAT-P-13b.

N_{tr}	BJD T_0 (LS)	BJD T_0 (RP)	ΔT_0+	ΔT_0-
269	2455564.39839	2455564.39892	0.00089	0.00271
279	2455593.56110	2455593.56085	0.00114	0.00115
280	2455596.47625	2455596.47610	0.00299	0.00311
281	2455599.39230	2455599.39252	0.00046	0.00105
282	2455602.31031	2455602.31038	0.00167	0.00166

Notes. The columns give: the “event number” N_{tr} for the transit following the ephemeris by Bakos et al. (2009), the central instant of the transit T_0 as estimated by a simple least squares fit (LS) and by the residual-permutation technique (RP), and the associated $1-\sigma$ uncertainties ΔT_0 (in days) as given by the RP distribution. BJD times are calculated from UTC.

pipeline that we specifically developed for the TASTE project. This code is designed to keep under control any possible source of systematic errors, and implements a fully empirical, iterative approach to identify and correct them. The output light curve is the one with the smallest effective RMS. Specific diagnostics are evaluated at each iteration to constrain the amount of correlated noise. The final, detrended light curves are shown in Fig. 1, both unbinned and binned over 120 s intervals. The photometric RMS scatter is in the range $\sigma_u = 1.7 - 2.9$ mmag for the unbinned points and the range $\sigma_{120} = 0.6 - 1.1$ mmag for the 120 s bins. Three of the light curves in Fig. 1 represent the most accurate light curves of HAT-P-13b published so far.

We ran the JKTEBOP code version 25 (Southworth et al. 2004) to fit a transit model over our light curves. We used a quadratic law for limb darkening, fixing both the linear and the quadratic term u_1, u_2 to the theoretical values interpolated from the Claret (2000) tables, for the stellar parameters of HAT-P-13 derived by Bakos et al. (2009). Three of the remaining parameters of the transit (inclination i , ratio, and sum of the fractional radii $R_a/R_b, R_a + R_b$) were estimated by fitting the two highest quality light curves (2011 Jan 3 and Feb 6). We then fixed $i, R_a/R_b, R_a + R_b$ to these respective values, and fitted each individual transit only for the central instant T_0 . Since the formal errors derived by the least squares routine are known to be far too optimistic, we took advantage of two techniques implemented in JKTEBOP to estimate realistic errors: a Monte Carlo test (MC) and a bootstrapping method based on the cyclic permutations of the residuals (RP or “prayer bead” algorithm, Southworth 2008). The errors from the RP algorithm are significantly larger, suggesting a non-negligible amount of red noise in our light curves. We therefore adopted conservatively the RP $1-\sigma$ errors in our analysis. The best-fit T_0 for each transit, converted from UT to barycentric Julian date (BJD), are shown in Table 2 along with their estimated uncertainties.

¹ <http://www.pd.astro.it/asiago/>

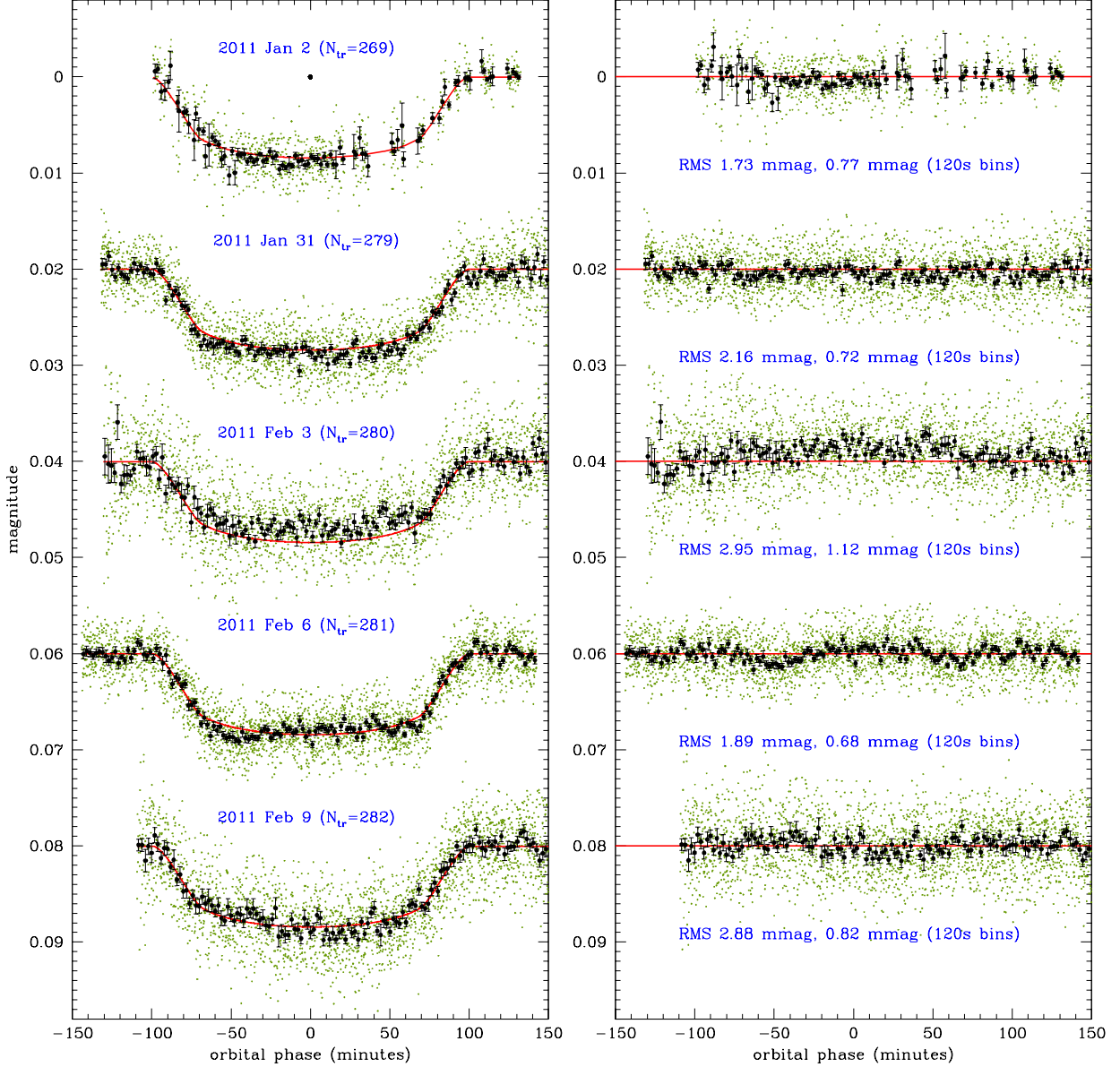


Fig. 1. (Left): Light curves of HAT-P-13b taken at the Asiago 1.82m telescope, for the five transit summarized in Table 2. The unbinned photometric points are plotted in green, the 120-s binned points are plotted in black. The red line is the best-fit model fitted by JKTEBOP. Transits have been offset by intervals of 0.02 mag for clarity. (Right): photometric residuals around the best-fit model.

4. Discussion

Our five timings points are very close in time to each other, four of them being consecutive transits ($N_{tr} = 258, 259, 260, 261$). They are consistent within the RP errors with a constant ephemeris ($O-C = +88, +0, -89, -79, +55$ s) that has a standard deviation of 78 s ($= 0.00090$ d). This is also an external approximate upper limit for our timing precision, and agrees well with the uncertainties ΔT_0 that we estimated.

In the top left panel of Fig. 2, we plotted our five new data points, along with the ones available from the literature (Bakos et al. 2009; Szabó et al. 2010; Pál et al. 2011) in a $O-C$ diagram using as a reference the ephemeris given by Pál et al. (2011). We confirm the timings of Pál et al. (2011), with ad-

ditional, more precise measurements. Our transits collected in January/February 2011 lie, respectively, 8.1σ , 13σ , 5.5σ , 22σ , and 8.9σ from the linear ephemeris fitted to the previous data. It is clear that an updated linear ephemeris cannot be fitted to all the available points with an acceptable χ^2 . No significant trend in the $O-C$ diagram is visible for the 2011 transits (Fig. 2, top right panel).

The two transits shown as red squares in the plots were observed under non-optimal weather conditions. During the first transit, “sky was photometric during the transit, but it was foggy in the evening and from 40 min after the egress phase”. During the second, “cirri were present that significantly affected the V band data, but the R light curve was well reconstructed” (from Szabó et al. 2010). Following a suggestion by an anonymous

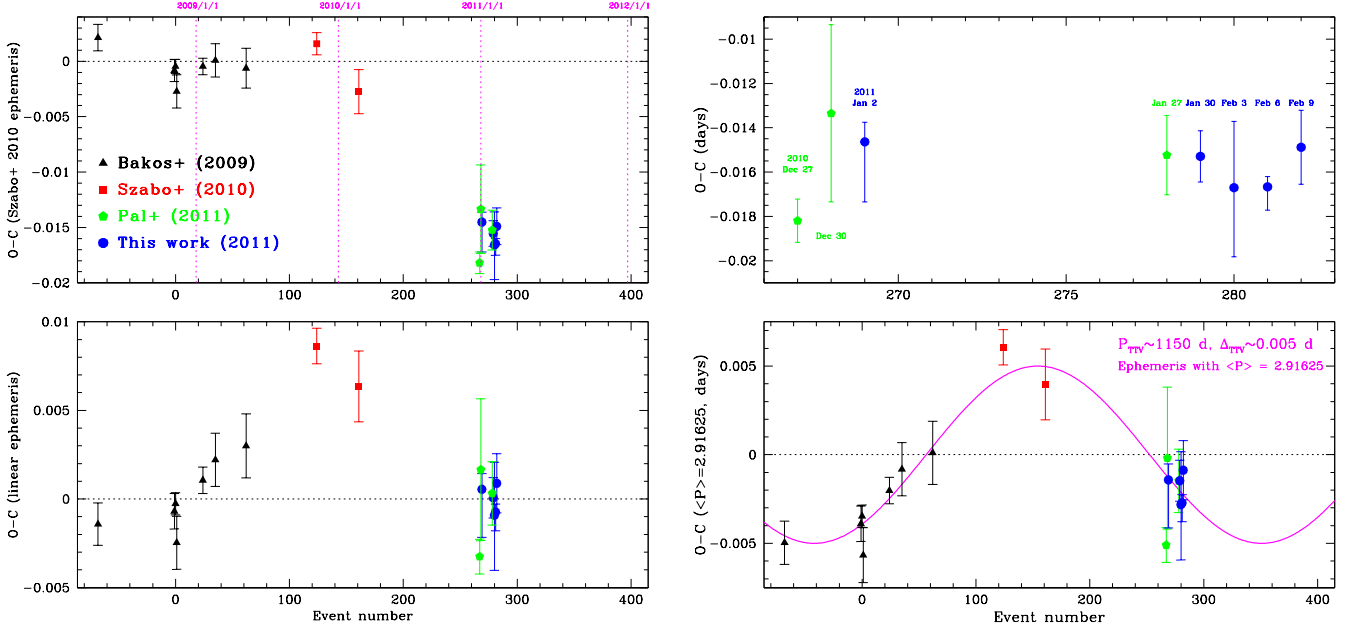


Fig. 2. *Top left:* $O - C$ diagram following the Pál et al. (2011) linear ephemeris. The new points from TASTE (Table 1) are plotted in blue filled circles. *Bottom left:* $O - C$ diagram following a linear ephemeris, fitted ignoring the two data points (red squares) from Szabó et al. (2010). *Top right:* Same as top left, zoomed on the transits collected in Jan-Feb 2011. *Bottom right:* the $O - C$ diagram folded over an ephemeris with $\langle P \rangle = 2.91625$ days, perturbed by a sinusoidal TTV with a period of $P_{\text{TTV}} = 1150$ days and an amplitude $\Delta_{\text{TTV}} = 0.005$ days.

referee, we checked whether a linear ephemeris can be properly fitted by ignoring these two data points (Fig. 2, bottom left panel). All of the first four transits by Bakos et al. (2009) lie at $O - C < 0$ (two by more than 1σ), while the second three transits lie at $O - C > 0$ (all by more than 1σ), suggesting a systematic trend. In any case, it seems unlikely that both the Szabó et al. (2010) data points are outliers, as they deviate in the same direction by a consistent amount (12.4 min = 8.6σ , and 9.1 min = 3.2σ respectively). They also come from observations carried out 108 days apart, made with two different telescopes by professional astronomers. As a cross-check, we also tried to compare the timings presented by Bakos et al. (2009), Szabó et al. (2010), and Pál et al. (2011) and by ourselves with data collected by amateurs available from the Exoplanet Transit Database (ETD). None of those twenty-two light curves are reliable for our analysis, being plagued to various extents by systematic errors: more than half of these data points deviate by more than $1-\sigma$ from a linear ephemeris. Though this TTV needs to be confirmed in a future season, present observational evidence points towards an indication of an anomaly in the periodicity of the transit.

We consider for a moment that the claimed TTV is real. As this TTV appears as a sudden switch of the ephemeris, Pál et al. (2011) suggested that this deviation in the $O - C$ diagram could be interpreted as a “spike” caused by a long-period eccentric perturber that is now near periastron. Examples of these systems can be found in the synthetic $O - C$ diagrams plotted by Holman & Murray (2005). This could explain why the 2008–2010 timing points are consistent with a linear ephemeris: such a perturber would have been far from HAT-P-13b, and its perturbative effects well within the measurement error. However, we note that the problem is still highly unconstrained, owing to the large errors and the uneven sampling of the previous measurements. Follow-up observations are required to constrain the

mass and the orbit of the perturber without huge degeneracies in the parameter space. In particular, we propose 1) to search for any unpublished measurements performed in March–November 2010, when the rising part of the spike could have been sampled and 2) to schedule new observations in October 2011–April 2012, to check whether the perturbation is still active, or the new timing points return to the original mean ephemeris.

To demonstrate that the measurements are consistent with different scenarios, we note that a periodic TTV cannot be excluded, in spite of the conclusions of Pál et al. (2011). We folded the $O - C$ diagram over an ephemeris that had an average period $\langle P \rangle = 2.91625$ days and had been perturbed by a sinusoidal TTV with an amplitude $\Delta_{\text{TTV}} = 0.005$ days and a period $P_{\text{TTV}} = 1150$ days (Fig. 2, last panel). This solution would be perfectly consistent with the available data, with only one outlier (the 2010 Dec 27 transit by Pál et al. 2011, 2.57σ from the best-fit solution), and compatible with the presence of an outer, coplanar, non-eccentric $5M_{\oplus}$ perturber locked in a 3:2 mean-motion resonance with HAT-P-13b, following the analytical approximations by Agol et al. (2005). This body could not have been detected by the RV measurements carried out so far. The observations that will be taken in October 2011–April 2012 will allow us to discriminate at least between this scenario and the “eccentric perturber” hypothesis, as a return to the original constant ephemeris would not be compatible with a periodic perturbation.

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